APPENDIX XXVIII

OIL SPILL ON-WATER RECOVERY

This appendix is under development (last update Oct 2008).

At this time this appendix only includes information about extant and evolving information for submerged oil response. There are only a few references to on-going efforts to studying the response to nonfloating oil and Chapter 3 excerpted from the 1999 National Academy of Science Report, Spills of Nonfloating Oil: Risk and Response.
http://books.nap.edu/catalog.php?record_id=9640 or http://www.nap.edu/catalog/9640.html

There is a working group involving various agencies, organizations, states, and counties attempting to advance response to nonfloating oils. This Submerged Oil Working Group is coordinated through the University of New Hampshire, Coastal Response Research Center (CRRC):

http://www.crrc.unh.edu/submerged_oil/index.htm

Lead point of contact is
Kathy Mandsager
Program Coordinator
Coastal Response Research Center
234 Gregg Hall, Colovos Rd
University of New Hampshire
Durham, NH 03824
603.862.1545
Kathy.mandsager@unh.edu

Submerged Oil Working Group Charge: improve understanding of behavior and fate of submerged oil and use it to improve response to and restoration after submerged oil spills

Four Focus areas have been developed:

- Detection and Monitoring
- Fate and Transport
- Containment and Recovery (including Protection of Water Intakes)
- Effects and Restoration

Currently CRRC is funding three related projects. Other projects are funded or underway in other organizations.

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Spills of Nonfloating Oils
Risk and Response

Committee on Marine Transportation of Heavy Oils
Marine Board
Commission on Engineering and Technical Systems
National Research Council

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Contents

Executive Summary

In the Coast Guard Authorization Act of 1996, the United States Coast Guard (USCG) was directed to assess the risk of spills for oils that may sink or be negatively buoyant, to examine and evaluate existing cleanup technologies, and to identify and appraise technological and financial barriers that could impede a prompt response to such spills. The USCG requested that the National Research Council (NRC) perform these tasks. In response to this request, the NRC established the Committee on the Marine Transportation of Heavy Oils.

Early in the committee's deliberations, it became clear that the statutory definition of Group V oils (oils with a specific gravity greater than 1.0) did not include all of the oils of concern. The first problem with using this definition is that specific gravity is defined as the ratio of the density of oil to the density of freshwater at a fixed temperature. The density of seawater, however, is slightly higher than that of freshwater and increases as salt content increases. Therefore, Group V oils could have lower densities than those of the receiving seawater and float. The second problem is that an oil with a specific gravity of slightly less than 1.0 (e.g., a Group IV oil) might mix into the water column and sink to the seabed after weathering and interaction with sediments. The committee, therefore, decided to use the term "nonfloating oils" to include all of the oils of concern based on their behavior. Nonfloating oils move below the sea surface either because of their initial densities or because of changes in their densities as a result of weathering or interaction with sediments. These oils may be just below the water surface, suspended in the water column, or deposited on the seabed.

In order to carry out the assessment, the committee gathered the available data on the transportation and spills of Group V oils, as well as data on other oils that are known to sink or become suspended in the water column when weathered or mixed with sediment. The data were available for asphalt, coal tar, carbon black, bunker C, and No. 5 and No. 6 fuel oils, (i.e., so-called “heavy oils”). The committee used the USCG’s (USCG) database on oil spills, refined with collaborative data from the Minerals Management Service (MMS), to develop estimates of the probability and mean size of oil spills. The U.S. Army Corps of Engineers (USACE) database on waterborne transportation of petroleum products and other cargoes over U.S. waters was used to assess the volumes of oil transported. The committee combined the spill statistics with the data on cargo tonnage to estimate historical rates on a barrel-per-ton-mile basis.

Historical spill rates must be modified for predictions of future spill rates because future rates will be influenced by fluctuations in traffic and trading patterns, as well as by changes in the ways vessels are designed and operated. The committee used the best available data, combined with its own collective judgment, to estimate the effects of these changes on the number and size of spills of nonfloating oils in the future.

Since 1991, the volume of oil spilled from vessels in U.S. waters has been reduced dramatically. Losses from tankers since 1990 have been less than one-tenth of the pre-1990 volume, and losses from barges have been less than one-third of the pre-1990 volume. From 1973 to 1990, there were 18 incidents involving spills of more than 25,000 barrels. Since 1991, there has not been a single spill of this magnitude for any category of oil. Nevertheless, very large spills will almost certainly occur some time in the future, although they are likely to be spills of crude oil rather than heavy oils, which tend to be transported in smaller volumes on barges and smaller tankers.

The USCG database includes descriptions of the substance spilled in each event. To estimate the frequency of spills of products with the potential to sink or become suspended in the water column after weathering or mixing with sediment, the committee summarized data for spills of more than 20 barrels for asphalt, coal tar, carbon black, bunker C, and No. 5 and No. 6 fuel oils. From 1991 to 1996, there was an average of 16 spills of these heavy oils per year, with an average volume of 785 barrels per spill. Tank barges were responsible for 28 percent of incidents and 80 percent of the volume of these spills of heavy oils. Most heavy-oil spills between 1991 and 1996 involved oils that were less dense than seawater, which only sink under unfavorable environmental conditions. The committee reviewed these heavy-oil spills with spill responders, who estimated that about 20 percent of these spills exhibited nonfloating behavior.

Most of the larger oil spills from land-based facilities were generally spills of crude oil or gasoline. The largest reported spill of heavy oil from a land-based facility between 1991 and 1996 was a spill of 929 barrels of No. 6 fuel oil into Pearl Harbor, Hawaii. By contrast, there were six tank-barge spills of more than 4,000 barrels involving heavy oil (either No. 6 fuel oil or slurry oil). The average volume of spills of heavy oil from barges was 2,254 barrels, and the largest was about 18,000 barrels. These spills were widely distributed geographically, with the highest frequency in the Gulf of Mexico.

Behavioral models have been developed for spills of nonfloating oils based on their physical and chemical properties. These descriptive, qualitative models predict how oils with densities near or above the density of the receiving water might behave. The models are based primarily on observations of oil spills. The committee described and assessed these models in terms of their effectiveness in predicting the behavior of nonfloating oils.

The environmental concerns associated with responses to spills of nonfloating oils are primarily related to water column and benthic (seabed) habitats. In most spills in open water, oil in the water column is unrecoverable, and response operations are limited to locating and monitoring its movement. However, if the suspended oil approaches shoreline habitats or nearshore benthic habitats in areas where current flow is minimal, the oil will sink and pool on the seabed. In these cases, an effective, but limited, response can be mounted, whereby a significant amount of oil can be removed from the seafloor. An effective response also includes removing oil from the shoreline, if and when it becomes stranded, to prevent its being eroded and sinking in nearshore tidal areas.

The behavior patterns of nonfloating oils can be complex, depending on the density of the oil, the density of the receiving water, and the physical characteristics of the spill site. Current technologies and techniques for locating, tracking, containing, and recovering spills of submerged oils include spill modeling and information systems, tracking and mapping techniques, and oil containment and recovery techniques. Chapter 3 focuses on the current state of practice and identifies systems that have been used or proposed for use in response to spills of nonfloating oils.

The containment and recovery of oil dispersed in the water column or deposited on the seabed is constrained by many factors, beginning with the difficulty of locating the oil and determining its condition. The success of current methods varies greatly but is usually limited because of the wide distribution of the oil and the fact that it is mixed with sediments and water. In general, available methods are most successful when the current speeds and wave conditions at the spill site are low (currents less than 10 cm/sec, wave heights less than 0.25 m), the oil is pumpable, the water is relatively shallow (water depths less than 10 m), and the sunken oil is concentrated in natural collection areas. The selection of methods for containment or recovery depends on the location and environmental conditions at the spill site, the characteristics of the oil and its state of weathering and interaction with sediments, and the equipment and logistical support available for the cleanup operation.

The committee identified a variety of barriers to responses to spills of nonfloating oils, including inadequate planning and training drills; lack of experience; lack of knowledge about transport, fate, and impact on the environment; the difficulty of locating and tracking oil suspended in the water column or deposited on the seabed; the limited technology options available for containment and recovery; and insufficient investment in research, development, testing, and evaluation of tracking, containment, and recovery systems.

FINDINGS

Finding 1. From 1991 to 1996, approximately 17 percent of the petroleum products transported over U.S. waters were heavy oils and heavy-oil products, such as residual fuel oils, coke, and asphalt. Approximately 44 percent was moved by barge and 56 percent by tanker.

Finding 2. From 1991 to 1996, approximately 23 percent of the petroleum products spilled in U.S. waters were heavy oils. In only 20 percent of these spills did a significant portion of the spilled products sink or become suspended in the water column. Most of the time, spills of heavy oil remained on the surface. The average number of spills of more than 20 barrels of heavy oil and asphalt was 16 per year, with an average volume of 785 barrels per spill. The committee projects that a 30 percent reduction in the number and volume of heavy-oil spills would have been realized if tankers and barges had all been double-hulled vessels.

Finding 3. In recent years, barges have had significantly higher spill rates than tankers. From 1991 to 1996, barges accounted for approximately 80 percent of the volume of heavy-oil spills, and the spill rate, expressed in terms of barrels-spilled-per-ton-mile, was more than 10 times higher for barges than for tankers. Although the reduction in spill volume from tank barges since 1990 has been significant (about one-third of pre-1990 volume), the reduction for tankers has been even more dramatic (about one-tenth of pre-1990 volume).

Finding 4. Specific gravity, as used in the regulatory definition of Group V oils, does not adequately characterize all oil types and weathering conditions that produce nonfloating oils. The committee was asked to address the issue of responses to Group V oil spills, defined by current regulations as oils with a specific gravity of greater than 1.0. However, the committee determined that the issue of concern is planning for and responding to oil spills in which most, or a significant quantity, of the spilled oil does not float. The committee, therefore, decided to use the term “nonfloating oils” to describe the oils of concern.

Finding 5. Nonfloating oils behave differently and have different environmental fates and effects than floating oils. The resources at greatest risk from spills of floating oils are those that use the water surface and the shoreline. Floating-oil spills seldom have significant impacts on water-column and benthic resources. In contrast, nonfloating-oil spills pose a substantial threat to water-column and benthic resources, particularly where significant amounts of oil have accumulated on the seafloor. Nonfloating oils tend to weather slowly and thus can affect resources for long periods of time and at great distances from the release site. However, the effects and behavior of nonfloating oil are poorly understood.

Finding 6. Although spill modeling and supporting information systems are well developed, they are not commonly used in response to nonfloating-oil spills because of limited environmental data and observations of oil suspended in the water or deposited on the seabed. Oil-spill models and supporting information systems are routinely used in contingency planning and spill responses. Sophisticated, user-friendly interfaces have been developed to take advantage of the latest advances in computer hardware and software. The current generation of models can rapidly incorporate environmental data from a variety of sources and include integrated geographic information systems. The models can also assimilate data on the most recently observed location of spilled oil and have improved forecasts of oil movements. They are not routinely used, however, in response to nonfloating-oil spills because of the lack of supporting data on the three-dimensional currents and concentrations of suspended sediments. Field data, such as oil concentrations in the water column and on the seabed, are also not generally available to validate or update models.

Finding 7. A substantial number of techniques and tools for tracking subsurface oil have been developed. Most of them, however, have not been used in response to actual oil spills. Many techniques are available for determining the location of oil both in the water column and on the seabed. These include visual observations, geophysical and acoustic methods, remote sensing, water-column and seabed sampling, *in situ* detectors, and nets and trawl sampling. The most direct and simplest methods, such as diver observations and direct sampling, are widely used, but they are labor intensive and slow. More sophisticated approaches, such as remote sensing, are limited to zones very near the sea surface because of technical constraints. Other advanced technologies, such as acoustic techniques, cannot differentiate between oil and water or between oiled sediments and underlying sediments. Many of the more sophisticated systems are prone to misuse and produce ambiguous data that are subject to misinterpretation. The performance of all but the simplest methods is undocumented either by field experiments or by use in spill responses.

Finding 8. Although many technologies are available for containing and recovering subsurface oil, few are effective, and most work only in very limited environmental conditions. Containment of oil suspended in the water column using silt curtains, pneumatic barriers, and nets and trawls is only effective in areas with very low currents and minimal wave activity. These conditions rarely exist at spill sites, particularly at sites in estuarine or coastal waters. The recovery of oil in the water column by trawls and nets is limited by the viscosity of the oil and net tow speeds.

The containment of oil on the seabed is typically ineffective, except at natural collection points (e.g., depressions and areas of convergence). The collection of oil on the seabed by manual methods, in natural collection areas and along the shoreline after beaching, is effective but labor intensive and slow. Manual methods are also limited by the depths at which diver-based operations can be carried out safely. Dredging techniques have rarely been used because of limited recovery rates, the large volumes of water and sediment generated, and the problems of storing, treating, and discharging co-produced materials.

Finding 9. The lack of knowledge and lack of experience, especially at the local level, in responding to spills of nonfloating oils is a significant barrier to effective response. The knowledge base and response capabilities for tracking, containing, and recovering nonfloating oils have not been adequately developed. Even at the national level, no system has been developed for sharing experiences or documenting the effectiveness and limitations of various options. With limited experience and a lack of proven, specialized systems, responders have found it difficult to adapt available equipment for responses to spills of nonfloating oils.

Finding 10. Planning for spills of nonfloating oils is inadequate at the local level. Existing area contingency plans do not include comprehensive sections on the risk of spills of nonfloating oils or how to respond to them. To date, planning has focused primarily on spills of floating oils. Inventories of equipment, lists of specialized services, assessments of the resources at risk, and protection priorities have not been developed by area committees for nonfloating oils. Nor have they identified the risks (e.g., transportation patterns, volumes, oil types), developed appropriate scenarios and response plans, or reviewed acceptable cleanup methods and end points. Existing plans have not been tested during drills or exercises to address deficiencies.

Finding 11. Funding levels for research, development, testing, and evaluation of spills of nonfloating oils are very low. The only active research programs currently under way either by government or industry groups are focused on emulsified fuel oils. Because the risk of spills of nonfloating oils is perceived as low relative to spills of floating oils, few research and development funds have been committed.

CONCLUSIONS

Conclusion 1. The tracking, containment, and recovery of spills of nonfloating oils pose challenging problems, principally because nonfloating oils suspended in the water column become mixed with large volumes of seawater and may interact with sediments in the water column or on the seabed. The ability to track, contain, and recover nonfloating oils is critically dependent on the physical and chemical properties of the oils and the water or the oils and the other materials dispersed in the water column or on the seabed. The differences in these characteristics are often quite small, and little technology is available for determining them.

Conclusion 2. Although many methods are available for tracking nonfloating oils, the simplest and most reliable are labor intensive and cover only limited areas. More sophisticated methods have severe technical limitations, require specialized equipment and highly skilled operators, or cannot distinguish oil from water or other materials dispersed in the water column. Engineered systems for containing oil in the water column or on the seabed are few and only work in environments with low currents and minimal waves. Natural containment in seabed depressions or in the lee of topographical or man-made structures on the seabed is effective for containing oils, but these are not always available in the vicinity of the spill.

Conclusion 3. The recovery of oil from the water column is very difficult because of the low concentration of dispersed oil; hence, recovery is rarely attempted. If oil collects on the seabed in natural containment areas, many options for effective recovery are available, although most of them are labor intensive and access to response equipment is a problem.

Conclusion 4. The volume and frequency of spills of nonfloating oils is significant (although smaller than for floating oils) and, therefore, should be an integral part of planning for spill responses, particularly in areas where nonfloating oils are regularly transported. Transport by tank barges raises particular concerns, given the relatively high spill rates from these vessels. The risks of potential harm to water-column and benthic resources from nonfloating oils have not been adequately addressed in the contingency plans for individual facilities or geographic areas.

Conclusion 5. Inland barges are subject to greater risks of spills than tankers and coastal barges; consequently, spill rates for barges are likely to be higher than for tankers. However, the large difference between the overall spill rates, as well as the decreasing number of spills from tankers in recent years (post-OPA 90), raises concerns regarding the performance of barges.

RECOMMENDATIONS

The recommendations below are intended to improve the capability of the spill response community to respond to spills of nonfloating oils.

Recommendation 1. The U.S. Coast Guard should direct area planning committees to assess the risk of spills of nonfloating oils (i.e., oils that may be dispersed in the water column or ultimately sink to the seabed) to determine the resources at risk. In areas with significant environmental resources risk, area planning committees should develop response plans that include consultation and coordination protocols and should obtain pre-approvals and authorizations to facilitate responses to spills. Stakeholder groups should be educated about the impact and methods available for tracking, containing, and recovering oil suspended in the water column or on the seabed. Area committees in locations where there is a high risk of spills of nonfloating oils should include at least one scenario for responding to a nonfloating-oil spill in their training or drill programs.

Recommendation 2. The U.S. Coast Guard should improve its knowledge base, education, and training for responding to spills of nonfloating oils by including a scenario involving a spill of nonfloating oils in oil-spill response drills, by establishing a knowledge base and scientific support teams to respond to these types of spills, and by disseminating this knowledge to the federal spill-response coordinators and area planning committees as part of ongoing training programs. The information would help area planners assess the requirements for responding to nonfloating-oil spills.

Recommendation 3. The U.S. Coast Guard should support the development and implementation of an evaluation program for tracking oil in the water column and on the seabed, as well as containment and recovery techniques for use on the seabed. The findings of these evaluations should be documented and distributed to the environmental response community to improve response plans for spills of nonfloating oils.

Recommendation 4. Tests of area contingency plans and industry response plans for responses to spills of nonfloating oils should be required parts of training and drill programs.

Recommendation 5. The U.S. Coast Guard should monitor spill rates from tank barges to ascertain whether current regulatory requirements and voluntary programs will reduce the frequency and volume of spill incidents. If not, the Coast Guard should consider initiating regulatory changes.

3

Technologies and Techniques

In this section, the current technologies and techniques for locating, tracking, containing, and recovering spills of nonfloating oils are summarized. The presentation is divided into subsections on spill modeling and information systems, spill tracking and mapping, and oil containment and recovery. The summary focuses on the current state of practice and identifies systems that have been applied or proposed for application to submerged oil. Summaries of the use of these techniques in selected spills in which substantial quantities of oil were submerged or deposited on the seabed can be found in Michel and Galt (1995) and Michel et al. (1995). An annotated bibliography of the literature can be found in NOAA (1997).

MODELING AND INFORMATION SYSTEMS

The following discussion begins with a brief overview of the state of the art in spill modeling and information systems (Box 3-1). This is followed by the extension of spill models to include the subsurface transport and deposition of dispersed oil and a history of the use of these models to "hindcast" (analyze a past event) several large accidental spills in which subsurface transport was important. The use of models to forecast and hindcast spills involving substantial amounts of submerged oil is then summarized.

Recent comprehensive reviews of the state of the art in spill modeling (Spaulding, 1995; ASCE, 1996) show that the models have evolved quite rapidly taking advantage of the availability of low-cost, high-powered workstations and personal computers with full color graphics, extensive storage, and communications systems. A simultaneous evolution in the software has enabled a clear

BOX 3-1
Oil-Spill Model

The core of an oil-spill model is a series of algorithms that represent the processes controlling the transport and fate of oil released into the environment. The transport portion of the models describes the physical movement of oil by winds, currents, waves, and associated turbulence. The fate of the oil is normally represented in terms of spreading, evaporation, dispersion or entrainment, dissolution, emulsification, biodegradation, sinking or sedimentation, photo-oxidation, and oil-shoreline and oil-ice interactions. These processes are typically formulated individually with links to other processes or environmental data as necessary to describe the oil's fate. The algorithms may be altered or changed entirely depending on the environment in which the oil is spilled or transported.

Input to oil-spill models normally includes a description of the study area, the oil-spill scenario (spill location, release rate and schedule, and oil type), and environmental conditions. The study area is normally described using a map of the region of principal interest. The environmental forcing data typically consist of estimates of the temporally and spatially varying wind and current fields for the forecast period (typically a few days for spill-response support) and an estimate of the mean water temperature. These environmental data fields may be provided by supporting hydrodynamic and meteorological models for the study area or from observations. The model output typically includes animations of the movement of the surface oil and the oil mass balance by major environmental compartments (surface, water column, onshore, evaporated, seabed, biodegraded), the oil thickness and areal extent, and the oil properties (viscosity, water content) versus time.

separation to be made between the model software and supporting environmental data (Spaulding and Chen, 1994). With model/data separation, the models can be rapidly applied to new locations (Anderson et al., 1993). Many models have been linked with geographic information systems (GISs) or have limited GIS functions embedded in the model systems (Galagan et al., 1992). With the incorporation of the GIS and other data management tools, users can input, organize, manipulate, archive, and display georeferenced information relevant to spill modeling. With the extension of spill models to include supporting data management tools, spill information systems have been developed that can provide valuable data to support spill responses and planning.

In most cases, models have been tested and validated by application to selected, usually large, accidental spills or experimental field trials. These events are selected based on the availability and quality of data. Hindcasts of the largest, most recent spills (*Exxon Valdez*, the Gulf War spill, *Braer*, *North Cape*) have been used by several researchers to demonstrate the predictive performance of their models.

Basic spill models have been extended to include biological and, in some cases, economic models for estimating the impact and damages of spills (e.g., French et al., 1994). These models are now being incorporated into comprehensive, on-scene, command-and-control systems (Anderson et al., 1998). Strategies for using models to prepare a trajectory analysis have been developed by Galt (1994, 1995). The National Oceanic and Atmospheric Administration (NOAA) has also developed digital distribution standards for data on trajectories (Galt et al., 1996).

Most of the spill models developed to date focus on the transport and fate of surface oil slicks. These models typically predict the mass of oil removed from the sea surface by evaporation, by dispersion or entrainment into the water column, and by sinking and sedimentation but do not explicitly track the dispersed oil. This approach has been taken because most spills involve oils that float throughout most of the short-term spill response. Selected models have the capability of predicting the three-dimensional evolution of oil, including entrainment, subsurface transport, sedimentation, and refloating of spilled oil (e.g., Spaulding et al., 1994; Elliot, 1991; Johansen, 1985; French et al., 1994). The majority of these models employ a particle-based, random-walk technique to predict the evolution of subsurface oil (Kolluru et al., 1994) although other alternatives have also been investigated (Spaulding et al., 1992). In these models, the influence of oil sediment interaction (Kirstein et al., 1985) and the buoyancy of dispersed oil droplets are explicitly accounted for.

The use of the three-dimensional models to forecast and hindcast spills has been limited. Most simulations have been restricted to buoyant oils that have been dispersed in the water column by strong winds or wave forcing. Although these oils are not a direct analog for nonfloating oils, they are instructive in illustrating the ability to predict the transport and fate of oil dispersed in the water column. For example, both Proctor et al. (1994) and Spaulding et al. (1994) performed hindcasts of the *Braer* spill. Both models correctly predicted the general subsurface transport of the highly dispersible, Gulfaks crude oil that was spilled. The predicted location of the subsurface oil was consistent with the pattern of sedimented oil found on the seabed. Neither hindcast included oil-sediment interaction, however, and no predictions were made of the deposition of sedimented oil.

A review of the literature on oil beneath the water surface and Group V oils by NOAA (1997) shows that spill models have generally not been used to forecast or hindcast spills of heavy oils. This is consistent with the summaries of spills of heavy oils presented in Michel and Galt (1995) and Michel et al. (1995). The absence of model applications to forecast or hindcast these events can be attributed to several factors. First, spills of heavy oils are generally less frequent, and the volume of oil spilled tends to be less than in spills of floating oils. Second, requirements for current data (either from observations or hydrodynamic model predictions), which are difficult to obtain for surface spills, are increased substantially when the subsurface transport of oil is involved. The subsurface current structure is of limited importance when the flows are principally tidal and water depths are shallow, but they become particularly important when stratification and multilayer flows are present. Finally, Michel and Galt (1995) have shown that substantial subsurface transport and deposition often occur as the result of the interaction of buoyant oil with sand. The sinking and subsequent deposition of oil caused by changes in the oil's density due to weathering (evaporative losses) or burning are rare (Lee et al., 1989, 1992).

Most spill models are focused on predicting the transport and fate of oil at sea and do not include oil-sediment interactions or oil-shoreline interactions. Given the lack of data and the lack of a clear understanding of the controlling processes, those that do are necessarily rudimentary (ASA, 1997; Reed et al., 1989). Incorporating oil-sediment interactions into spill models will require estimates of the suspended sediment concentrations as input (Kirstein et al., 1985). These estimates are normally based on observations or model predictions, and the data are rarely available during spill events. Incorporating oil-shoreline interactions will require extensive data on the nearshore environment, including geomorphology and wave and current fields. Once again these data are generally not available for most spills, particularly during the emergency response phase.

Given this situation, two strategies might be tried to use existing spill models to assist in the response to spills where subsurface transport processes and sinking and sedimentation might be important. First, the spill model could be used to explore the impact of various assumptions about the subsurface transport of the oil and the interaction of oil and sediment. For example, it could be assumed that a portion of the oil will be removed or leave the surface as it becomes neutrally bouyant or sinks at a specified rate due to oil-sediment interaction. Model predictions could then be made to estimate the path and a general sense of the area and volume that would be impacted by the subsurface oil. The information could be used to establish field sampling programs. Data collected from the field on the current structure and sediment concentrations could then be used to refine the predictions and narrow the scope of the uncertainty.

A second approach would be to place the spill model in real-time operation for the principal areas of concern. Supporting three-dimensional hydrodynamic and sediment-transport models for nearshore and offshore areas would provide currents and suspended-sediment fields for inputs to the spill model. The models, which would have been validated with field observations, would be able to assimilate real-time data from monitoring systems to maximize their predictive performance. This approach would only be viable for areas where the probability of spills is high enough to warrant the investment in the development, application, and maintenance of such a system.

TRACKING AND MAPPING TECHNIQUES

Techniques for tracking and mapping the location of oil throughout a spill and subsequent cleanup are critical to the effective containment and recovery of oil in the water column or deposited on the seabed. A brief summary of current methods for tracking and mapping subsurface oil follows. The review is based primarily on summaries in Castle et al. (1995) and Michel et al. (1995). Additional information is available in Smedley and Belore (1991) and Brown et al. (1997). As a practical guide to determining which tracking and mapping options are most appropriate, Figure 3-1 provides a typical decision tree based on oil density and water depth. The first branching is based on assessing the density of oil relative to the density of the receiving water and includes two branches, one if the oil is neutrally buoyant and one if the oil is negatively buoyant in receiving water. The second branching depends on the water depth. Final selection of the tracking method is dependent on local conditions, the availability of equipment and personnel, and weather conditions.

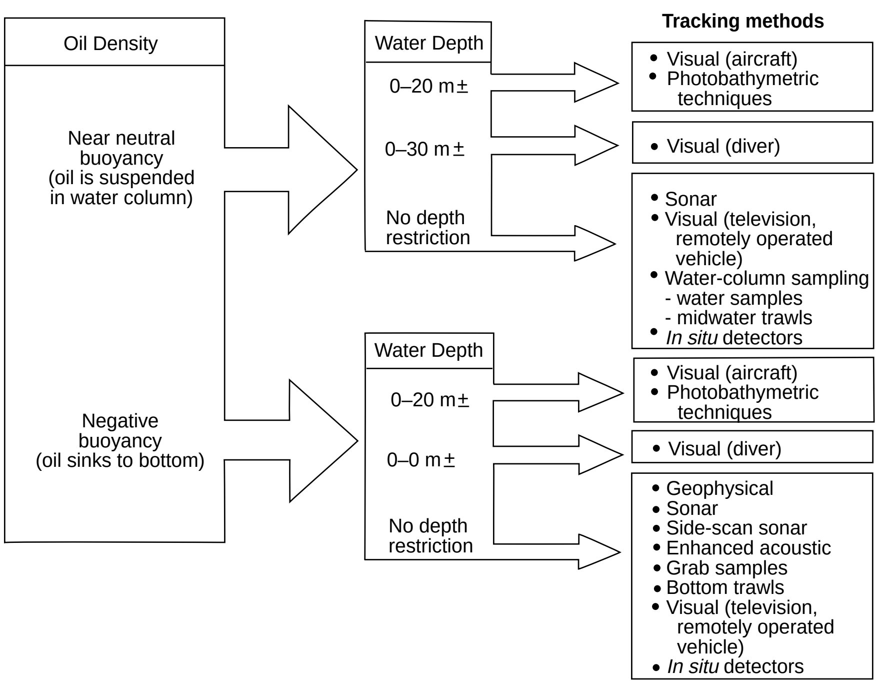

FIGURE 3-1 Decision tree based on oil density and water depth. Source: Castle et al., 1995.

Visual Observations

Visual observations (by aircraft, ship, diver, or camera/television) have been the principal methods of locating and tracking submerged oil. Airborne photography and visual-based systems, which are widely available and can rapidly survey large areas, are widely used to locate submerged oil. The performance of these systems is limited by water clarity and depth, the quantity of oil, and the characteristics of bottom sediment. Given the possibility of misidentifying natural materials (seaweed, seagrass beds) as oil, *in situ* observations are always required to validate airborne assessments. Direct observations can also be performed by divers within safe depth restrictions and visibility limits. Observations by underwater cameras, either operated by divers or deployed from ships, can also be used to locate submerged oil. These visual methods must generally be confirmed by sampling and have relatively limited coverage. As an extension of visual methods, photobathymetric techniques, such as multispectral photography, may be useful for mapping oil on the seabed in shallow water (Benggio, 1994b). Once again, field confirmation and calibration are required.

Remote Sensing Techniques

Standard, side-looking, airborne radar, synthetic-aperture radars, and infared/ultraviolet line scanners are generally unable to map subsurface oil because they cannot penetrate the water surface (Fingas and Brown, 1996). The methods are also hindered by the weather and visibility. Laser fluorosensor techniques have been developed and shown to be able to detect oil in the water column for the purposes of oil exploration (Dick and Fingas, 1992; Dick et al., 1992). Little evidence exists that this technique has been used in responding to spills of nonfloating oils, however (Brown et al., 1997). Recent laboratory experiments by Brown (1998) have demonstrated a laser airborne fluorosensor that can detect the presence of dispersed bitumen in the water. No field tests or practical uses of the system have been made to date.

Geophysical/Acoustic Techniques

These technologies include of a variety of acoustic-based techniques for locating and mapping submerged oil (Chivers et al., 1990). These techniques rely on acoustic sounding principles, specifically the differential density and sound speeds of water compared to those of oil or oil-sediment mixtures and the scattering of sound waves from particulate material in the water column. Oil in the water column can be qualitatively mapped by commercial fish-finding and echo sounders or by precision survey equipment. Oil on the seabed and associated bottom features can be mapped by side-scan sonar systems. The output of these systems can be enhanced for mapping the texture and composition of the bottom.

One such system was reportedly used to map the submerged oil from the *Morris J. Berman* and *Haven* spills (Marine Microsystems, 1992).

Side-scan sonar mapping systems are normally interfaced with the global positioning system (GPS) and hydrographic mapping software to generate maps of seafloor features. These systems can provide relatively rapid coverage but are most useful when they are used to direct the surveys for areas of natural collection that have already been identified. These specialized systems may be unable to distinguish between oiled sediments and underlying sediments because of their acoustic similarity. Therefore, sampling or *in situ* observations are necessary to confirm the maps.

Water-Column and Bottom Sampling

Direct sampling of the water column or seabed may be used to locate and map the movement of oil. Sampling can be done by a vessel, a remote vehicle, or a diver (in shallow water). Sampling generally becomes more difficult and time consuming as the water depth, current speed, and wave height increase. A variety of sampling techniques are available, including grab sampling of water or sediments with subsequent visual or chemical analysis, sorbent materials deployed on weighted lines or in traps (Benggio, 1994a), and core sampling of the seabed sediments. Sampling is typically limited in scope and may not provide representative observations of the impact area. Water-column and bottom trawls may be useful for selected spills because they can cover larger areas. The effectiveness of sampling methods is strongly dependent on the composition of the oil and oiled sediment and environmental factors, such as current speed, water depth, and substrate type.

In Situ *Detectors*

In situ and towed fluorometric detection are widely available and routinely used to detect and map petroleum leaks and spills (Turner Designs, 1999). These systems may be mounted on buoys, boats, or remotely operated vehicles. When mounted on boats and coordinated with GPS, they can provide maps of the subsurface oil concentration field. They are restricted to making oil concentration measurements in the water column (Brown et al., 1997) and have a detection range from parts per billion to parts per million, depending on environmental conditions and oil type. Given the three-dimensional nature of submerged oil plumes, mapping of subsurface oil requires an extensive effort. Towed systems might also be used to monitor conditions at one location, such as in a river, to determine whether oil has reached that location and is being transported downstream. These systems have historically been used to assess the effectiveness of dispersants in field trials and planned spill events. They have not been routinely used for actual spills in the United States but are used in Canada and the United Kingdom to assess the potential for tainting fish from subsurface oils.

Summary

The appropriate method for tracking and mapping a particular spill depends on whether the oil is suspended in the water column or deposited on the seabed and on the water depth and clarity. In general, visual and photobathymetric techniques are restricted to water depths of 20 meters or less and are suitable for both suspended and deposited oil. Diver-based visual observations can only be used in low-current and small wave areas. Acoustic techniques, television observations, water-column and bottom sampling, *in situ* detectors, and nets and trawls typically have no depth restrictions except that the water must be deep enough for the instrument to be deployed and operated safely. They become more difficult to operate, however, as the current speed and wave height increase. Measurements near the seabed become more challenging as the topographic relief of the bottom increases and the bottom surface becomes rougher. Tables 3-1 and 3-2 provide a summary of the uses and limitations of various tracking and mapping methods.

CONTAINMENT AND RECOVERY METHODS

The following descriptions summarize the current state of practice for containing and recovering heavy oils. The summary is based principally on work by Michel et al. (1995), Castle et al. (1995), and Benggio (1994c). Additional information is available in Bonham (1989), and Moller (1992). A useful summary of the containment and recovery of sinking hazardous chemicals is presented in Boyer et al. (1987). Brown et al. (1997) provide a useful summary of the practical aspects of containing and recovering spills of “sunken and submerged oils” and also summarize the methods used in successful responses to spills. Supporting data on these successful responses can be found in NOAA (1997).

Protocols for determining which methods to use for a given spill situation have been proposed by Castle et al. (1995). The approach is based on a decision tree structure, with the principal branching being determined by the buoyancy of the oil, the depth of the water column, and whether the oil is pumpable or not. Figures 3-2 and 3-3 show decision trees for the containment and recovery of sunken oil, respectively. Criteria for each branch are also provided. The form of the decision tree is similar to the one for tracking and mapping (see Figure 3-1).

Containment

Oil that is spilled and transported subsurface either remains suspended in the water column or is deposited on the seabed, usually after interaction with suspended sediments or sand. Different strategies for containing these oils can be used depending on the location of the oil. Typical response strategies are described below. Few of these techniques have been used and their performance has not been documented during spill events.

Oil in the Water Column

*Silt Curtains***.** The containment of oil suspended in the water column is generally possible only in areas with weak currents (less than 10 cm/sec) and small waves (less than 0.25 m). Silt curtains, which are normally used to control the transport of suspended sediment during dredging operations, are typically restricted to water depths of 3 to 6 meters and are deployed so that the bottom of the curtain does not extend to the seabed. They have not been used in actual spill events.

*Nets and Trawls***.** Midwater trawls and nets may be used for containing selected oil types in certain conditions. The performance of these systems depends on the viscosity of the oil and being able to locate and concentrate the oil. Delvigne (1987) has suggested that nets can successfully contain oil if the currents are low (less than 10 cm/sec) and the viscosity of the oil is high. Nets can be towed, moored, or mounted on moving floats. This method is sometimes used to protect fixed structures (water intake systems) or resources at risk. The effectiveness of trawls and nets declines rapidly as current speeds increase or as nets become clogged. During the *Presidente Rivera* spill in the Delaware River, fish nets were able to recover eight tons of oil before they became fouled (NOAA, 1992).

*Pneumatic Barriers and Booms***.** Pneumatic barriers involve injecting air at the seabed and forming a bubble plume that rises to the surface. Pneumatic barriers have been considered for protecting seawater intakes against oil dispersed in the water column, but little data are available for assessing their performance. Standard oil booms (deep draft) have been considered for containing subsurface oil. In fact, booms have been suggested as the preferred option for responding to spills of bitumen-surfactant-water mixtures and have undergone limited testing at sea (Deis et al., 1997; Sommerville et al., 1997). Booms can be used only when the oil remains in the upper water column, the currents are low (less than 0.20 m/sec), and the waves are small (less than 0.25 m).

Oil on the Seabed

*Seabed Depressions***.** Oil deposited on the seabed can be moved by ambient currents and waves. Sedimented oil tends to collect in natural or man-made depressions on the bottom, including natural and dredged channels, wave-generated troughs offshore of sandy beaches, and natural depressions. Dredging to create depressions for oil collection is not practical as part of a spill response except for very large spills or spills that have very substantial benthic impacts.

TABLE 3-1 Options for Tracking Oil Suspended in the Water Column

	Visual Observations	Water Sampling
Description	Trained observers in aircraft or on vessels look for visual evidence of suspended oil; includes use of cameras.	Visual inspection or chemical analysis of grab water samples or a flow-through system with a fluorometer.
Availability of Equipment	Uses readily available equipment.	Uses readily available equipment and supplies.
Logistical Requirements	Low/aircraft and vessels are readily available during spill response.	May require boat, sampling equipment, pumps, GPS for station location, portable oil analyzer.
Coverage Rate	High for aircraft; moderate for vessels.	Very low coverage rate; collecting discrete water samples at multiple depths for testing is very slow.
Data Turnaround	Quick turnaround.	Quick turnaround for visual analysis; chemical results would have to be available in minutes to be effective.
Probability of False Positives	High probability, due to poor water visibility, cloud shadows, seagrass beds, irregular bathymetry, mixing of different waterbodies.	Low probability; field personnel would have to know how to operate all equipment.
Operational Limitations	Requires good water visibility and light conditions; poor weather may restrict flights; limited to daylight hours.	Realistic only for water depths <30 ft; sea conditions may restrict vessel operations.
Pros	Can cover large areas quickly using standard resources available at spills.	Can be used at points of concern, such as water intakes.
Cons	Only effective in areas with very low water turbidity.	Too slow to be effective in dynamic settings or over large areas.

Fish Net Trawls	Sorbent Fences	Airborne Imaging LIDAR
Fish nets or trawling gear are towed for set distances then inspected for presence of oil; or nets can be set at fixed points and regularly inspected.	Sorbents are attached to something like a chain link fence which is submerged into the water then pulled for inspection; or it could be set at a fixed point for regular inspection	Pulsed laser and video recording system compares back-reflectance from below the water surface for areas of suspended oil versus clean water. Detection depth varies (nominally 45 ft). Operable 24 hours/day
Readily available in commercial fishing areas.	Uses readily available equipment and supplies	Uses very specialized equipment of limited availability
Moderate; requires boat and operators to tow the nets; may require multiple vessels to cover large areas; may require many replacement nets as they become oiled.	Low; can be deployed from small boats or carried to small streams for deployment	Moderate; equipment must be modified for mounting on local aircraft; requires skilled operators
Low coverage; nets have a small sweep area and must be pulled frequently for inspection.	Low; they have a small sweep area and they have to be pulled frequently for inspection	High; flown on aircraft with 200 ft swath
Quick turnaround.	Quick	Moderate; data recorded on video
Low probability; oil staining should be readily differentiated from other fouling materials.	Low; sorbents are designed to pick up oil, so they would be less likely to be stained by other materials	High; system images all submerged features, have to learn to identify patterns for different features, thus requires extensive ground truthing
Obstructions in the water can hang up nets; restricted to relatively shallow depths; sea conditions may restrict vessel operations.	Difficult to deploy and retrieve in strong currents; sea conditions may restrict vessel operations	Weather may restrict flights; minimum detectable size of oil particle is not known, but other individual features detected are usually feet in size or schools of small fish
Can sweep various depths or very close to the bottom.	Uses material available anywhere	Can cover large areas quickly using standard resources available at spills; permanent record of image that is geo-referenced
Very slow; nets can fail from excess accumulation of debris.	Very slow; very limited sampling area	Not proven for detecting suspended oil droplets; very limited availability

TABLE 3-2 Options for Mapping Oil Deposited on the Seabed

	Visual Observations	Bottom Sampling from the Surface	Underwater Surveys by Divers
Description	Trained observers in aircraft or on vessels look for visual evidence of oil on the bottom; includes underwater cameras.	A sampling device (corer, grab sampler, sorbents attached to weights) is deployed to collect samples from the bottom for visual inspection.	Divers (trained in diving in contaminated water) survey the sea floor either visually or with video cameras.
Availability of Equipment	Uses readily available equipment.	Uses readily available equipment and supplies	Underwater video cameras are readily available, but divers and diving gear for contaminated water operations may not be available locally.
Logistical Needs	Aircraft and vessels are readily available during spill response.	Requires boat, sampling equipment, GPS for station location.	Depend on the level of diver protection required.
Coverage Rate	High for aircraft; low for vessels.	Very low coverage; collecting discrete bottom samples is very slow; devices sample only a very small area.	Low coverage, because of slow swimming rates, limited diving time, poor water quality.
Data Turnaround	Quick turnaround.	Quick turnaround because visual analysis is used.	Quick turnaround.
Probability of False Positives	High, due to poor water clarity, cloud shadows, seagrass beds, irregular bathymetry.	Low probability, except in areas with high background oil contamination.	Low probability because divers can verify potential oil deposits.
Operational Limitations	Requires good water clarity and light conditions; weather may restrict flights; can be used only during daylight hours.	Sea conditions may restrict vessel operations.	Water depths of 20 m (for divers); minimum visibility of 0.5–1m; requires low water currents.
Pros	Can cover large areas quickly using standard resources available at spills.	Can be effective in small areas for rapidly definition of a known patch of oil on the bottom; low tech option; has been proven effective for certain spills.	Accurate determination of oil on bottom; verbal and visual description of extent and thickness of oil and spatial variations.
Cons	Only effective in areas with high water clarity; sediment cover will prevent detection over time; ground truthing required.	Samples a very small area, which may not be representative; too slow to be effective over large area; does not indicate quantity of oil on bottom.	Slow; difficult to locate deposits without GPS; decontamination of diving gear can be costly/time consuming.

Bottom Trawls	Photobathymetry	Geophysical/Acoustic Techniques
Fish nets or trawling gear are towed on the bottom for set distance then inspected for presence of oil.	Aerial stereo photography mapping technique used to identify and map underwater features (a realistic scale is 1:10000).	Sonar system that uses the differential density and sound speeds in oil and sediment to detect oil layers on the bottom; a fathometer records a single line under the sounder; side-scan sonor records a swath; output can be enhanced to increase detection.
Readily available in commercial fishing areas.	Available from most private aerial mapping companies, with specifications.	Requirements vary; often not available locally; need trained personnel.
Requires boat and operators to tow the nets; may require multiple vessels to cover large areas; may require many replacement nets as they become oiled.	Aircraft specially equipped to obtain vertical aerial photography with GPS interface.	Requires boat on which equipment can be mounted; requires updated charts so that search area can be defined.
Low coverage; nets have a small sweep area and they have to be pulled up frequently for inspection.	High coverage.	Moderate coverage; data collected at speeds up to m/s.
Quick turnaround.	Slow turnaround.; aerial photographs can be produced in a few days in most places; data interpretation takes one or two additional days.	Medium turnaround; data processing takes hours; preliminary data usually available next day; requires ground truthing.
Low probability; oil staining should be readily differentiated from other fouling materials.	High probability; photography can be used to identify potential sites, which require ground truthing.	High probability; identifies potential sites but all need ground truthing.
Obstructions on the bottom can hang up nets; restricted to relatively shallow depths; sea conditions may restrict vessel operations.	Specifications call for low sun angles and calm sea state; water penetration is limited by water clarity; maximum penetration is 10m for very clear water,1m for turbid water; best if baseline “before” photography is available for comparison.	Sea conditions must be relatively calm to minimize noise in the record.
Can provide data on relative concentrations on the bottom per unit trawl area/time; can survey in grids for more representative areal coverage.	Rapid assessment of large areas; high spatial resolution; good documentation and mapping.	Can be used to identify potential accumulation areas; complete systems can generate high-quality data with track lines, good locational accuracy.
Very slow; nets can fail from excess accumulation of debris.	Limited by water clarity, sun angle, and availability of historic photography for comparisons.	Data processing can be slow; requires extensive ground truthing; requires skilled operators.

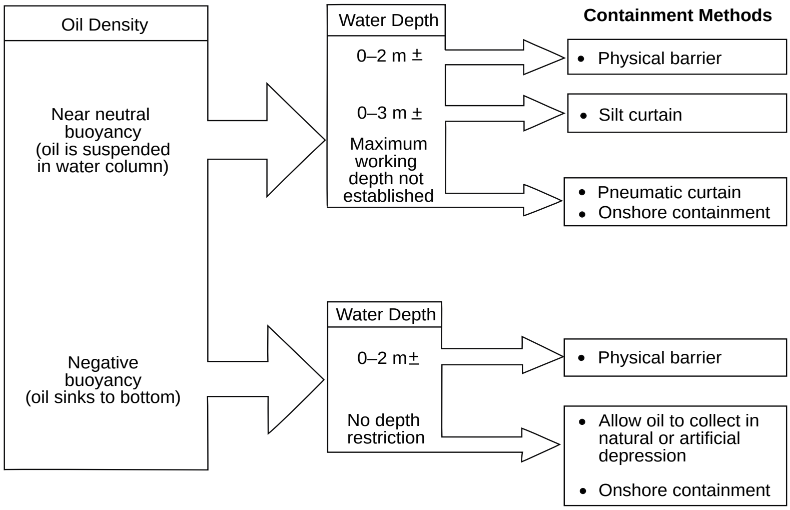

FIGURE 3-2 Decision tree for containment options for sunken oil. Source: Castle et al., 1995.

Identification of natural depressions and collection points, however, may be very useful for locating sedimented oil and planning for its recovery.

*Bottom Booms***.** Bottom-mounted boom systems could be used to contain oil on the seabed. The booms could be moored to the seabed and flotation used to maintain the vertical structure of the boom. These systems are only suitable for locations with low currents and little wave activity. No practical applications of these systems have been reported.

Recovery

The recovery of sunken oil has proven to be very difficult and expensive because the oil is usually widely dispersed. Several of the most widely used recovery methods are reviewed below.

Manual Removal

The manual removal of oil, one of the most widely used recovery methods, involves divers or boat-based personnel using dip nets or seines to collect oil, which is temporarily stored in bags or containers. The purpose of manual recovery is to remove the oil and minimize the collection, handling, treatment, storage, and disposal of other material (oiled sediment, sediment, and water). This approach can be useful for widely dispersed oil, and its effectiveness can be assessed by

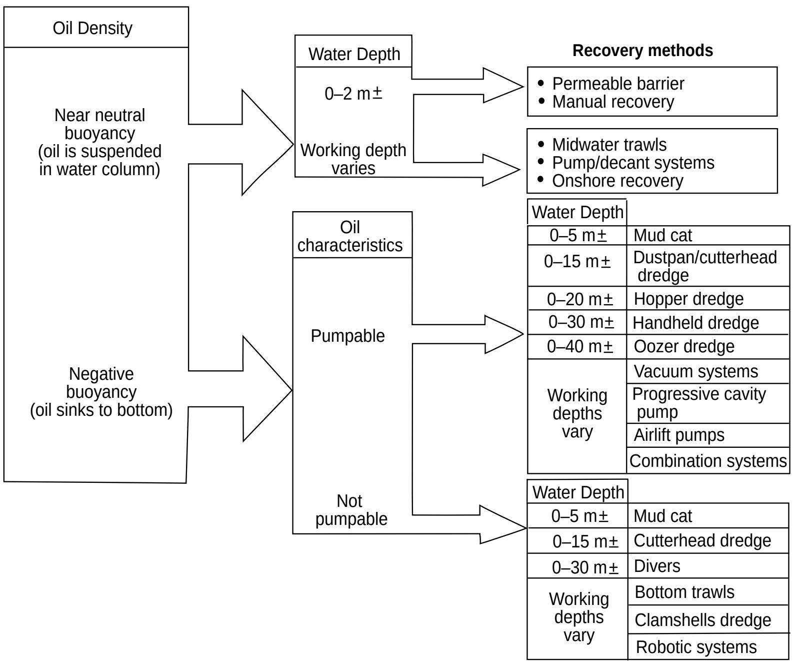

FIGURE 3-3 Decision tree for recovery options for sunken oil. Source: Castle et al., 1995.

cleanup standards or criteria. The biggest disadvantages of manual removal are the large manpower and logistical requirements, slow rates of recovery, strong dependency on weather conditions, and the potential for the oil to be transported while it is being recovered.

Pump and Vacuum Systems

These systems have historically been most successful for removing large volumes of sunken oil. They typically consist of a submersible pump/vacuum system, an oil-water separator, and a storage container. The systems can be mounted on trucks, on land, or on barges or ships. The suction head of the system is normally directed and controlled by divers and may have an air or water injection system to assist in fluidizing and transporting the slurry. The pumped material is usually a mixture of water, oil, and oiled sediment. Highly viscous or solid oils are usually not pumpable and, hence, are not recoverable with this method.

High-energy pumping systems cannot be used because of their potential for breaking up oil droplets or globules and emulsifying the oil. The pumped mixture is typically routed to an oil-water separator from which the oil and oiled sediment are removed and stored. The water may be stored for treatment or released into the sea. Oil-water separation may be difficult if the recovered oil is denser than the recovered water. Pumps and vacuum systems are effective if the oil is localized but are not practical for large areas. They also require extensive equipment and the capacity to handle and treat large volumes of water and sediments.

Nets and Trawls

In addition to containing dispersed oil, nets and trawls can also be used as collection devices (Brown and Goodman, 1987; Delvigne, 1987). This approach is most successful when the relative velocity of the water and the oil collected in the net or trawl is low and the viscosity of the oil is high. The effectiveness decreases as the permeability of the net is reduced and flows are diverted around the net (Delvigne, 1987).

Dredging

Dredging is an efficient, well developed method for removing large volumes of sediment (and oil) from the seabed at high recovery rates. Castle et al. (1995) provide a summary of the operating characteristics of a wide variety of dredging systems routinely considered for the removal of sunken oil. Additional information on the feasibility of dredging for the cleanup of sunken oil is given in Bonham (1989). Large volumes of water, oil, and sediment are typically generated in the dredging process and must be handled, stored, and disposed of as the recovery operation proceeds. Accurate vertical control of the dredge depths is critical to minimizing the amount of dredged material and the amount of clean sediment contaminated with oil as the result of the dredging operation. Operational costs and logistics requirements are lower for land-based than for barge-based methods of handling and storing dredged materials. Given the potential for storms that increase freshwater flows and shipping traffic, both of which can resuspend or remobilize sunken oil, the timeliness of dredging is crucial.

Onshore Recovery

In some cases, oil that has been submerged and mixed with sediment enters the surf zone and is eventually moved onshore and deposited on the shoreline. In these cases, conventional shoreline cleanup methods can be used to remove the oil.

Summary

The containment and recovery of oil dispersed in the water column or deposited on the seabed are very difficult. The problem begins with locating the oil and determining its status. The success of current methods varies greatly but is usually

TABLE 3-3 Options for Containing Oil Suspended in the Water Column

	Pneumatic Barriers	Net Booms	Silt Curtains
Description	Piping with holes is placed on the bottom, and compressed air is pumped through it, creating an air bubble barrier.	Floating booms with weighted skirts (1-2 m long) composed of mesh designed to allow water to pass while containing suspended oil.	During dredging operations, silt curtains are deployed as a physical barrier to the spread of suspended oil; weighted ballast chains keep the curtain in place.
Availability of Equipment	Uses readily available equipment, although in unique configuration.	There are commercially available net booms have been developed and tested for containing spills of Orimulsion; little availability in the United States.	Not readily available; limited expertise in deployment and maintenance.
Logistical Requirements	Moderate; requires a system to deploy and maintain bubbler; piping has tendency to clog; high installation costs.	Moderate; similar to deployment of standard booms, but with added difficulty because of longer skirt; can become heavy and unmanageable.	Moderate; deployment and maintainance.
Operational Limitations	Only effective in low currents (< 0.2 m/sec), small waves, and shallow water >2 m.	In field tests, the booms failed in currents <0.75 knots; very limited few conditions.	Only effective in very low currents(<10cm/sec); practical limits on curtain depth are 3–6m, which normally doesn't extend to the bottom.
Optimal Conditions	To contain oil spilled in dead-end canals and piers; to protect water intakes.	Will contain oil only in very low-flow areas, such as dead-end canals and piers.	Still water bodies such as lakes; dead-end canals.
Pros	Does not interfere with vessel traffic.	Can be deployed similar to traditional booms.	Can be deployed throughout the entire water column.
Cons	Only effective under very limited conditions; takes time to fabricate and deploy, thus only effective where pre-deployed; little data available to assess performance.	Only contains oil suspended in the upper water column, to the depth of the mesh skirt; unknown whether the mesh will clog and fail at lower currents.	Effective under very limited conditions, not likely to coincide with location where oil needs containment; oil droplets are larger than silt and could clog curtain.

TABLE 3-4 Options for Recovering Oil Deposited on the Seabed

	Manual Removal by Divers	Nets/Trawls
Description	Divers pick up solid and semi-solid oil by hand or with nets on the bottom, placing it in bags or other containers	Fish nets and trawls are dragged on the bottom to collect solidified oil
Equipment Availability	Contaminated-water dive gear may not be locally available	Nets and vessels readily available in areas with commercial fishing industry
Logistical Needs	Moderate; diving in contaminated water requires special gear and decon procedures; handling of oily wastes on water can be difficult	Low; uses standard equipment, though nets will have to be replaced often because of fouling
Operational Limitations	Water depths up to 60-80 ft for routine dive operations; water visibility of 1-2 ft so divers can see the oil; bad weather can shut down operations	Water depths normally reached by bottom trawlers; obstructions on the bottom which will hang up nets; rough sea conditions; too shallow for boat operations
Optimal Conditions	Shallow, protected areas where dive operations can be conducted safely; small amount of oil; scattered oil deposits	Areas where bottom trawlers normally work; solidified oil
Pros	Divers can be very selective, removing only oil, minimizing the volume of recovered materials; most effective method for widely scattered oil deposits	Uses available resources; low tech
Cons	Large manpower and logistics requirements; problems with contaminated water diving and equipment decon; slow recovery rates; weather dependent operations	Not effective for liquid or semi-solid oil; nets can quickly become clogged and fail; can become heavy and unmanageable if loaded with oil; could require many nets which are expensive

limited because the oil, which is mixed with sediments and water, is usually widely dispensed. In general, the success is greatest when the current speeds and wave conditions at the spill site are low, the oil is pumpable, the water depths are relatively shallow, and the sunken oil has concentrated in depressions or collection areas. The selection of containment and recovery methods is highly dependent on the specific location and environmental conditions during the spill, the

Pump and Vacuum Systems (Diver-directed)	**Dredging**
Divers direct a suction hose connected to a pump and vacuum system, connected to oil-water separator, and solids containers. Viscous oils require special pumps and suction heads. Even in low water visibility, divers can identify oil by feel or get feedback from top-side monitors of changes in oil recovery rates in effluents	Special purpose dredges, usually small and mobile, with ability for accurate vertical control. Uses land or barge-based systems for storage and separation of the large volumes of oil-water-solids.
Readily available equipment but needs modification to spill conditions, particularly pumping systems, and capacity for handling large volumes of materials during oil-water-solids separation	Varies; readily available in active port areas; takes days/week to mobilize complete systems
High, especially if recovery operations are not very close to shore. On-water systems will be very complicated and subject to weather, vessel traffic, and other safety issues.	High, especially if recovery operations are not very close to shore, because of large volumes of materials handled. On-water systems will be very complicated and subject to weather, vessel traffic, and other safety issues.
Water depths up to 60-80 ft for routine dive operations; water visibility of 1-2 ft so divers can see the oil; bad weather can shut down operations; solid oil which is not pumpable	Min/max water depths are a function of dredge type, usually 2-100 ft; not in rocky substrates; bad weather can shut down operations
Sites adjacent to shore, requiring minimal on-water systems; liquid or semi-solid oil; thick oil deposits, good visibility; low currents	Large volume of thick oil on the bottom; need for rapid removal before conditions change and oil is remobilized, buried by clean sediment, or will have larger environmental effects
Most experience is with this type of recovery; diver can be selective in recovering only oil and effective with scattered deposits;	Rapid removal rates; can recover non-pumpable oil
Very large manpower and logistics requirements, including large volumes of water-oil-solids handling, separation, storage, and disposal; problems with contaminated water diving and equipment decon; slow recovery rates; weather dependent operations	Generates large volumes of water/solids for handling, treatment, disposal; large logistics requirements; could re-suspend oil/turbidity and affect other resources

characteristics of the oil and its state of weathering and interaction with sediments, the availability of equipment, and logistical support for the cleanup operation. In addition, the potential environmental impacts of implementing these methods, particularly in sensitive benthic habitats, must be considered. Tables 3-3 and 3-4 summarize the uses and limitations of various containment and recovery methods.

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